Weather files for remote places

Leveraging reanalyses and satellite datasets

Daniel Fosas, Manuel Herrera, Sukumar Natarajan, David A. Coley
EDEn – Department of Architecture and Civil Engineering
University of Bath
Bath, United Kingdom

***Abstract*— Weather files capture the time-varying conditions under which buildings perform and, as such, they constitute one of the fundamental inputs for building performance simulation. In theory, the creation of weather files only requires collecting data at a certain frequency for a key number of variables during the time of interest. In practice, several problems arise. Direct measurement on a project basis can be a costly operation considering the site accessibility and the number of instruments needed to collect complete weather observations. Sometimes, this is simply impossible if a study requires historical data. These issues are traditionally overcome using the weather data collected at a nearby public weather stations, but this can be equally challenging, or even impossible, depending on how far away the station is and the frequency and completeness of observations.**

Arising from the need to simulate the thermal performance of buildings at remote locations, this study presents an approach to generate weather files based on satellite imaging and reanalysis datasets. Given the good agreement with local station's observations, it is shown how these publicly available datasets can be combined to create weather files suitable for building performance simulation. This is applied to a case study to compare the performance of a building and its systems against traditional weather files. The work quantifies and discusses the discrepancy obtained between the different sources. Overall, results indicate that satellite and reanalysis datasets constitute a suitable resource to create weather files for building performance simulation.

Keywords*— *building simulation; weather files; satellite data; built environment; building physics

I. Introduction

One of the fundamental roles buildings have is the provision of indoor environments in which human activity can thrive, given a changing outdoor environment that is frequently uncomfortable and, at times, even inhospitable. This requires buildings that mediate successfully the energy exchange between these environments, a task they can accomplish through two mechanisms: passive energy transfers and active energy counterbalances. Among others, the former involves adequate envelope characteristics and occupant behavior; the latter fueled systems that, in the pursuit of adequate indoor environments, currently account for 10% of the total energy consumption in the world [1], [2]. Therefore, and regardless of the mechanism employed, the external environment is at the core of the energy exchanges that drive building design, operation and energy consumption [3].

In the last decades, building performance simulation (BPS) has been established as a prominent tool for researchers, policy makers and professionals due to the influence buildings have not only on occupants' health and well-being, but also on the economy and carbon emissions [4], [5]. Following a conceptualized model of the mechanisms that arise in real life, one of the central inputs for BPS is a representation of the environment surrounding building components [4], [6]. This has been, over time, parametrized in the so-called 'weather files', files that describe the most basic and relevant environmental variables in a model (e.g. air temperature, relative humidity, solar radiation, wind characteristics) [7], [8].

Despite the role weather files play, one of the barriers yet to overcome is their worldwide coverage and availability. The creation of weather files requires collecting data for the essential variables for the problem at hand, and at a certain frequency, with weather stations [3], [7]–[9]. This is typically achieved using weather stations of the World Meteorological Organization (WMO [10]) given the difficulties and costs associated with private weather monitoring. However, the spatial and temporal distribution of these stations—and the suitability of the data they collect to create weather files—vary greatly. A weather station might not be close enough to the location of interest to accurately describe weather conditions, there might be missing variables or values (e.g. solar radiation), the frequency of records might be unsuitable for BPS (e.g. daily means), there might even be no records at all for the time span of interest, or a combination of all the previous.

These issues have motivated a large body of research to maximize the amount of usable weather information for weather files (e.g. [11]–[15]). Research projects and organizations have analyzed data resources and applied a variety of models and assumptions to this extent, but their land coverage still features serious limitations, depending on the location of interest, and often require a paid license [3], [9], [16]–[18]. Building on these efforts, and thanks to the collaboration of many institutions, the U.S.A. Department of Energy (DOE) offers one of the most popular services that index freely available weather files [19], [20]. An overview of this resource shows a total number of 2,590 weather files, that is, a world average of 1 weather file per a 227-kilometer-side square in land [19], [21]. This is clearly insufficient to capture the weather variability between locations. Yet, these figures largely depend on the country under consideration. For instance, the U.S.A. features 1,478 weather files (57% of the dataset), while other countries a have a substantially smaller coverage, if any.

Sponsors: EPSRC projects 'Healthy Housing for the Displaced' ['HHftD', grant number EP/P028175/1], and 'The creation of localized current and future weather for the built environment' ['COLBE', grant number EP/021890/1]. Daniel Fosas gratefully acknowledges the financial support by the 'laCaixa' foundation and the University of Bath.

Parallel to these developments and discussions, there has been active monitoring campaigns of the Earth's climate. As a result, there are products available that have resulted from direct and indirect measurements, local and remote, or derived through the new and refined models based on these campaigns. The promising advantages of these resources are their vast spatio-temporal coverage, consistency, quality assurance and public availability. However, routinely applications to weather files as a whole in BPS could not been found in the surveyed literature, albeit notable exceptions: the use of satellite solar radiation data [9], [11], [18], ASHRAE's numerical model to adjust weather observations [22] and the work by Lundström for Northern Europe based on mesoscale datasets [23], [24]. Unfortunately, it is unknown if and how weather files can be generated based on these kinds of datasets and how they compare to the traditional approach based on weather stations.

Due to these limitations and opportunities, this work hypothesizes that large-scale datasets resulting from the Earth's monitoring campaigns and models can be used to create weather files for BPS. In particular, the objectives are to discuss the creation of weather files based on these datasets and their comparison against traditional weather files from public and private resources. A case study is carried out based on a residential model and the needs of the 'Healthy Housing for the Displaced' project (HHftD) to simulate the performance of buildings that are often located in remote locations.

The work is organized as follows. Firstly, the creation of weather files for a common BPS engine is discussed, suitable data resources are identified, and the case study is introduced. Next, the results and discussion are presented and structured around three aspects: (1) the comparison of weather observations between the local weather station of the HHftD project and those found in the new resources, (2) the application of the nearest publicly available weather files against their independent recreation with the new datasets and (3) overall performance of the new weather files for the remote location against seven weather files from two independent sources. Lastly, section IV presents the concluding remarks.

II. METHODOLOGY

A. Weather files for building performance simulation

Among all the available options, Energy Plus Weather files (EPW) constitute the most popular weather file format for BPS [8] and is thus taken as the reference format for this study. The EPW format was proposed in 1999 to overcome the limitations already experienced with previous approaches, and it established the weather file format for two open-source and well-validated BPS engines widely used in research, ESP-r and EnergyPlus [7]. Besides these, nowadays other BPS software accept this weather file format, either directly or indirectly via conversion (e.g. IES, TRNSYS, DesignBuilder, TAS).

The EPW specification is open and based on a loosely defined schema implemented as a comma-separated value text file. Therefore, EPW files are transparent to the user and can be readily inspected. Internally, the file is divided into two sections, a 'header' and a 'body'. Components and fields are identified by the position they occupy since most are unlabeled [7], [14].

The header comprises the first 8 lines of the EPW and it describes: (1) the location of the weather file, including name, region, country, type of weather file, WMO station ID, latitude, longitude, time zone and elevation; (2, 3) a brief description of design and typical/extreme weather conditions, which could be used, for example, to size building systems; (4) thermal characteristics of the ground its monthly average temperatures; (5) a description of holidays and daylight saving periods; (6, 7) space reserved for arbitrary comments; (8) a summarized description of the data in the second section, the 'body'.

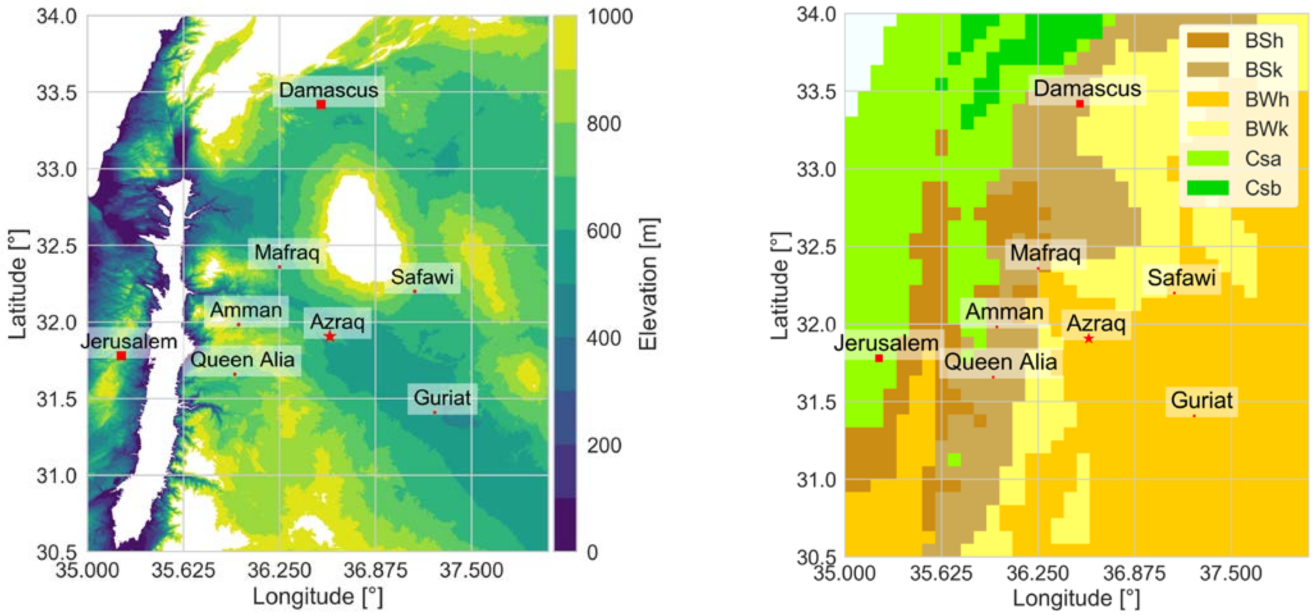
The body spans from line 9 onwards and it describes the actual observations time series. These are provided for variables that can change significantly between timesteps, together with source and uncertainty metadata. For example, the body includes variables such as air temperature, solar radiation and wind, whereas ground temperatures are described in the header with monthly values. The frequency and number of observations is flexible, although hourly observations over a year is a common choice (i.e. 8760 or 8784 records for leap and non-leap years, respectively). The minimum number of variables (columns) in the body is 33 and the maximum 35, where the last 3 columns provide complementary information for selected variables (see [7], [14] for a comprehensive list).

Two key remarks are important for this work. Firstly, not all the information present in a weather file is necessarily used by a BPS software. Secondly, missing values can be specified for selected fields. This means that the actual interpretation of an EPW file unavoidably relies on the BPS engine used. Here, the engine EnergyPlus is chosen to continue the discussion and carry out the study, given that the widespread use this software has in research and commercial applications, its open-source code and its tight integration with the EPW format.

As of the latest stable version available at the time of this work (version 8.9), the following observations can be made regarding the use of EPW and the aims of this study. These are based on the documentation, crosschecked with the source code and tested with sample cases and selected EPW files from ASHRAE. Whenever missing or contradictory information was found, the source code version prevailed.

1. The information in the EPW header can be overwritten by the EnergyPlus model as they often depend on the building or site characteristics rather than weather.

2. The following time series variables are used by EnergyPlus: (1, 2) Date and time information; (3) dry bulb temperature; (4) dew point temperature; (5) relative humidity; (6) atmospheric pressure; (7) horizontal infrared sky radiation (if missing, it can be estimated through the opaque sky cover); (8, 9) direct and diffuse solar radiation; (10, 11) wind direction and wind speed. In addition, surface convection and reflectance models need to know if surfaces are wet and if there is snow on the ground. If present, this information is derived from one or more of the following columns: (12) present weather observations, (13) present weather codes, (14) snow depth and (15) liquid precipitation depths. Otherwise, EnergyPlus defaults to dry surfaces and no snow conditions.



a) Elevation (values clipped to 0–1000m range, out-of-range values in white; elevation data from [30])

b) Köppen-Geiger climate zone classification (climate zone data from [31], [32])

Fig. 1. Locations considered in the study (symbols: the ‘star’ indicates the location of interest; ‘dots’ the closest commercial weather files; ‘squares’ two of the closest publicly available weather files; plot grid as per MERRA-2 structure)

B. *Alternatives to weather station data for weather files: the MERRA-2 and CAMS datasets (‘ReaSat’)*

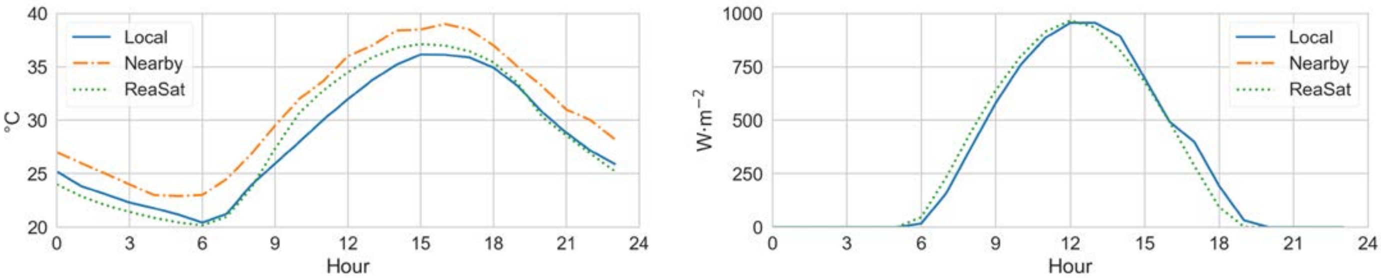
Given the information required, two products have been identified to construct the essential information for EPW files in EnergyPlus. The first is the MERRA-2 presented by Gelaro et al. in 2017 [25]. MERRA-2 is a comprehensive reanalysis of a wide number of observing systems. This means that different observations are integrated into a resource that, via a forecast model, produce a coherent dataset with homogeneous spatial coverage [25]. MERRA-2 data is publicly available, and it features worldwide gridded variables at about 50km, in hourly intervals since 1980 [26]. The following variables are directly obtained: air temperature, relative humidity, atmospheric pressure, wind direction, wind speed, rainfall and snow depth. The dew-point is then obtained through phsychrometric relationships. Lastly, the present weather observations and codes are adjusted according to rainfall and snow depth.

The second product identified for the creation of weather files is the ‘Copernicus Atmosphere Monitoring Service’ radiation service version 3 (here referred to as ‘CAMS’) [27]. This service integrates satellite observations through a series of models to create a comprehensive dataset for solar radiation, and atmospheric composition [28]. Data is available from February 2002 onwards, and the spatial coverage of this service is roughly the area comprised between ±66° for both longitudes and latitudes in a 3-kilometer grid. For this study, data at 1-minute intervals were used to obtain the remaining variables for the EPW file. The variables retrieved here are: global, diffuse and direct solar radiation, cloud coverage and albedo. It must be noted that not all of them are strictly required for the EPW. Yet, the cloud coverage allows the calculation of the horizontal infrared sky radiation, the albedo informs inputs for the BPS model surroundings and the global horizontal radiation can be compared to weather station observations, as shown in the next sections. The main limitation is that the albedo and cloud coverage are derived variables from solar radiation observations and they are not available at night time. As an approximation, they were filled in via linear interpolation.

C. *Case study*

To fulfill the aims of this work, a case study is devised based on the location of the refugee camp of Azraq (Jordan, Fig. 1). The weather at this location is partly monitored by the HHftD project given that the nearest WMO weather stations are approximately 60km way. Commercial weather files are available based on those WMO stations, which fill any gaps in observations through a number of models [18]. Lastly, the closest freely available weather files for this location are those of Jerusalem and Damascus (approximately 130 and 180km away from Azraq, respectively; IWEC EPW files [16], [17]).

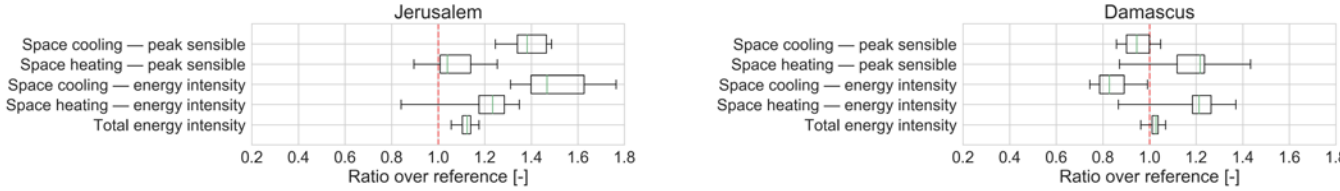
Despite the large number of variables captured in weather files, they do not impact building performance equally. Bearing in mind that MERRA-2 and CAMS are routinely validated, the interest here lies in quantifying how different is the performance of a building under weather files derived from these sources (here termed ‘ReaSat’ weather files) when compared against traditional approaches (weather files around the location of interest). For this, the detached house prototype at DOE [29] was adapted to EnergyPlus v8.9 and simulated under these different weather files versions. The selected model version was that for the 2006 International Energy Conservation Code, located in Phoenix (Arizona) and with a heat pump. The reasons for this choice are that Phoenix’s climate (BWh) is the same as Azraq’s and that the heat pump provides both space cooling and heating. Therefore, this allows the comparison of building performance in cold and hot seasons and avoids the modelling complexities of naturally ventilated buildings.



a) External dry bulb temperature ('ReaSat' values from MERRA-2)

b) Global horizontal radiation
(n.b. missing data for 'nearby' case, 'ReaSat' values from CAMS)

Fig. 2. Comparison of time series summarized in an 'average day' (monitoring period: from 2017-08-10 until 2017-08-20; 'local': on-site weather station, 'nearby': nearest WMO station (WMO 402650, 60km away from the location), 'ReaSat': obtained from MERRA-2 and CAMS data).



a) Jerusalem

b) Damascus

Fig. 3. 'ReaSat' 2005–2017 vs nearby IWEC weather files (boxplot convention: bar within the box represents the median, the box the range between first and third quartile and the whishkers the min-max range; data normalize with the performance obtained for the original IWEC weather file for the variable at hand)

III. Results and Discussion

A. 'ReaSat' versus on-site and nearby weather stations

Both MERRA-2 and CAMS are gridded datasets at 50-km and 3-km intervals, respectively. Hence, the first potential concern is their spatial representativeness within a grid cell. Although data could be adjusted in several ways, it is still of interest their comparison against on-site observations.

The results on Fig. 2 compare observations for two of the most important weather variables in BPS. In Fig. 2-a, the 'ReaSat' version provides a better fit for the local observed values than the one obtained with 'nearby' WMO station (near Safawi). Noting that the WMO station is further into the desert (Fig. 1), this disagreement is deemed reasonable. Traditional goodness-of-fit metrics allow quantifying the disagreement between two signals. The mean bias error (MBE), a measure of the overall average disagreement, yields 1% for the 'ReaSat-Local' pair, and 8% for the 'Nearby-Local' one. Similarly, the coefficient of variation of the root mean square error (CV(RMSE)) provides a measure of the disagreement of values at time-step level, resulting in 4% for 'ReaSat-Local' and 9% for 'Nearby-Local' pairs.

Fig. 2-b shows a frequent situation where solar radiation data is not available in a nearby weather station. Yet, the agreement between the on-site monitored values and those obtained for the 'ReaSat' version is remarkable ($MBE \approx 0\%$; $CV(RMSE) \approx 14\%$) and better than those typically accepted in modelled solar radiation for weather files to decompose global horizontal into diffuse and direct components [13].

Although the on-site monitoring period is limited (10 days), these results indicate good agreement between local measurements and the MERRA-2/CAMS observations. Overall, the latter was a preferable alternative to WMO station data.

B. 'ReaSat' versus selected IWEC weather files

A second test for the new weather files is the recreation of existing ones. Fig. 3 shows the results for the two cases under consideration, Jerusalem and Damascus. The same kind of weather file (IWEC) was chosen for both locations to simplify the analysis. IWEC files are one of the many approaches to create 'typical year' weather files: files that attempt to capture average weather conditions for a location based on a mixture of observations from several years. For this study, the main problem is that these files are based on historical weather data prior to 2002 and is thus outside CAMS temporal coverage. An alternative approach is taken based on 13 individual weather files corresponding to the years 2005–2017. Assuming IWEC files faithfully represent a typical year, the closer the 2005–2017 'ReaSat' simulation are to that of the IWEC one, the greater the confidence in the new weather file generation framework.

Results are twofold. Those for Jerusalem show a poor agreement with the reference IWEC weather file (Fig. 3-a) whereas those for Damascus show a good overlapping between the 'ReaSat' 2005-2017 range and the reference values (Fig. 3-b). Reasons for this outcome can be given on Fig. 1. There, it is shown how site characteristics within the MERRA-2 grid cell for Jerusalem vary greatly. The elevation spans a wide range, from negative altitudes in the Dead Sea to elevations around 800m (Fig. 1-a). Likewise, the climate classification features two different main climatic zones in the same grid cell (Fig. 1-b). Contrarily, the case for Damascus benefits from more homogeneous characteristics within its grid cell, although it is influenced by the Anti-Lebanon mountain range in the North.

Up until now, results suggest that MERRA-2 displays a reasonable approximation for average weather conditions, but care must be taken in heterogeneous grid cells. This could be tackled in several ways, like the application of spatial interpolation techniques, but this falls out the scope of this study.

C. 'ReaSat' weather files for remote locations

Fig. 4 presents the comparison of the model performance under 'ReaSat' weather files to the ones obtained with conventional nearby weather files. Having shown that 'ReaSat' can provide useful observations for weather files, this addresses a common issue for BPS modelling: the building at hand is at considerable distance of the closest available data sources. Three basic strategies are usually employed: (1) choosing the closest freely available weather file (here, Jerusalem), (2) choosing the closest freely available weather file under a similar climate (here, Damascus) or (3) turn to commercial options (here, the remaining locations shown in Fig. 1 around Azraq).

Although the total energy intensity is reasonably consistent across locations, this is not necessarily the case for its breakdown (Fig 4). For example, Jerusalem has notable differences in performance when compared to every other case. The smaller values for space cooling energy intensity and peak cooling power can be understood in Fig. 1, as it is shown that Jerusalem belongs to an entirely different climate zone with cooler temperatures. In this sense, the performance of the multi-year 'ReaSat' version of Azraq closely agrees with that of Damascus, where boxplot ranges overlap for every metric. This emphasizes the preferable match of climatic conditions when choosing a weather file rather than blind direct proximity.

The performance obtained in Guriat and Safawi can also be attributed to geographical differences. These locations are at a lower elevation than Azraq, and deeper within the desert. The result is a remarkable higher cooling energy intensity and power requirements. Likewise, Queen Alia, Amman and Mafraq show substantial differences with Guriat and Safawi in these regards. This is especially noteworthy because all these weather files are of the same type and generated by the same procedures.

Overall, the general pattern obtained for 'ReaSat' weather files in Azraq can be deemed reasonable, especially considering the different weather file types involved in the analysis. The 13-year simulation appears to capture a weather variability that compares in magnitude to the differences obtained across every other location. In addition, this range overlaps well with the arguably most similar locations to Azraq. Given the choices modelers need to make for BPS in these circumstances, no fundamental reasons are found to discourage the careful use of reanalysis and satellite-derived datasets.

IV. CONCLUSSIONS

This study presents a novel framework to create weather files for building simulations based on satellite imaging and reanalysis datasets. Motivated by the need to estimate the thermal performance of buildings in remote locations, this approach promises greater freedom for the creation of weather files than their counterparts based on weather station data. The method is thus compared to on-site and off-site weather observations, and a series of building simulation experiments quantify the effects of the new weather files against traditional ones around the location of interest.

The analysis that underpins this framework stresses the importance weather files have in building performance simulation, and exposes aspects often neglected due to the limitations in data

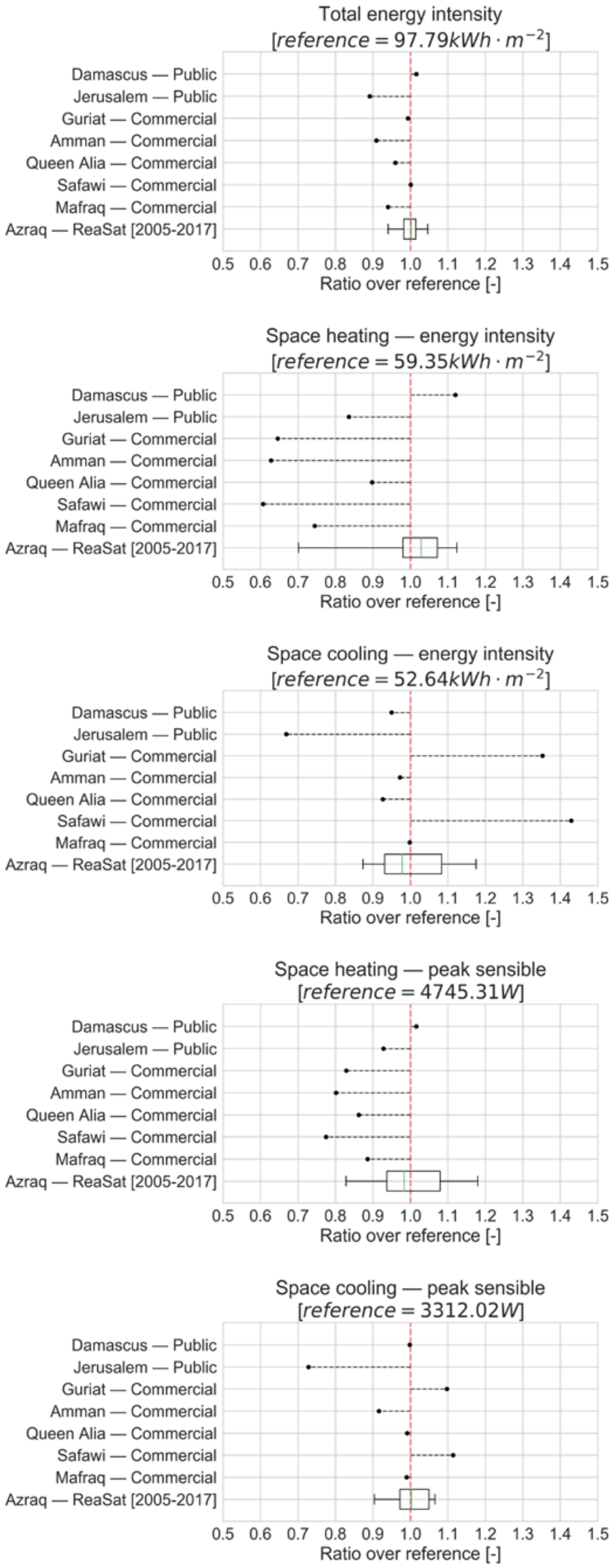


Fig. 4. Building performance comparison under different weather files (the reference taken to normalize values in each plot is the average of the multi-year simulation of the 'Azraq — ReaSat [2005–2017]' case; see Fig. 3 for boxplot conventions)

availability. Unless weather observations are made at the very location under study, there is room for large variations. In this sense, weather files with this new framework appear as a reasonable approach if the conditions within the grid cell are sensibly homogeneous. In these circumstances, the inter-agreement of the new weather files is not only coherent with that of similar locations but also with on-site measurements. In addition, it provides a closer fit to that obtained with of the off-site public weather stations considered in this study. If conditions in the grid cell are heterogeneous, there are several ways to continue forward. For instance, common techniques in environmental sciences could be applied to localize observations to the very point of interest.

Nevertheless, and despite its simplicity, the framework can be regarded as a starting point to enhance current input data practices in building performance simulation. The duplicity of sources would then mean a greater confidence in weather files (un)certainties that modelers can leverage to inform decisions that help deliver buildings that do perform as intended.

Acknowledgments

We thank Shaghayegh Mohammad and Dima Albadra for their help in acquiring local weather data in Jordan, and Nick McCullen for the computational resources used in this study. Local weather station monitoring in Azraq conducted in collaboration with Princess Sumaya University of Technology in Jordan, UNHCR Jordan and NRC Jordan. Besides the referenced work, the study was conducted thanks to open-source software, specially EnergyPlus, Python and NumFOCUS projects, and the outstanding communities behind them.

References

[1] IEA and OECD, *Transition to sustainable buildings strategies and opportunities to 2050*. Paris: OECD/IEA, 2013.

[2] International Energy Agency, 'IEA Sankey Diagram', 2018. [Online]. Available: https://www.iea.org/sankey/. [Accessed: 01-Mar-2018].

[3] Chartered Institution of Building Services Engineers, *Environmental Design: CIBSE Guide A*, 8th ed. London: Chartered Institution of Building Services Engineers, 2017.

[4] J. A. Clarke, *Energy simulation in building design*, 2nd ed. Oxford: Butterworth-Heinemann, 2001.

[5] Chartered Institution of Building Services Engineers, *Building performance modelling*. London: Chartered Institution of Building Services Engineers, 2015.

[6] D. B. Crawley *et al.*, 'EnergyPlus: creating a new-generation building energy simulation program', *Energy and Buildings*, vol. 33, no. 4, pp. 319–331, 2001.

[7] D. B. Crawley, J. W. Hand, and L. K. Lawrie, 'Improving the weather information available to simulation programs', in *Proceedings of Building Simulation'99*, 1999, vol. 2, pp. 529–536.

[8] M. Herrera *et al.*, 'A review of current and future weather data for building simulation', *Building Services Engineering Research and Technology*, pp. 1–26, 2017.

[9] American Society of Heating Refrigerating and Air-Conditioning, *2017 ASHRAE handbook: Fundamentals*. 2017.

[10] A. Smith, N. Lott, and R. Vose, 'The Integrated Surface Database: Recent Developments and Partnerships', *Bulletin of the American Meteorological Society*, vol. 92, no. 6, pp. 704–708, Jun. 2011.

[11] J. L. M. Hensen and R. Lamberts, Eds., *Building Performance Simulation for Design and Operation*. London: Routledge, 2011.

[12] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, 'Modeling daylight availability and irradiance components from direct and global irradiance', *Solar energy*, vol. 44, no. 5, pp. 271–289, 1990.

[13] P. Ineichen, R. Perez, R. Seal, E. Maxwell, and A. Zalenka, 'Dynamic global-to-direct irradiance conversion models', *ASHRAE Transactions*, vol. 98, no. 1, pp. 354–369, 1992.

[14] Ernest Orlando Lawrence Berkeley National Laboratory, 'EnergyPlus Documentation', 2016. [Online]. Available: http://nrel.github.io/EnergyPlus/. [Accessed: 10-Oct-2016].

[15] C. P. Underwood and F. W. H. Yik, *Modelling Methods for Energy in Buildings*. Oxford: Blackwell Publishing, 2004.

[16] D. J. Thevenard and A. P. Brunger, 'The development of typical weather years for international locations: Part I, algorithms', *ASHRAE Transactions*, vol. 108, p. 376, 2002.

[17] D. J. Thevenard and A. P. Brunger, 'The development of typical weather years for international locations: Part II, production/Discussion', *ASHRAE Transactions*, vol. 108, p. 480, 2002.

[18] Meteonorm, 'Meteonorm: Features', 2018. [Online]. Available: http://www.meteonorm.com/en/features. [Accessed: 01-Mar-2018].

[19] National Renewable Energy Laboratory, 'Weather Data Sources', 2018. [Online]. Available: https://energyplus.net/weather/sources. [Accessed: 01-Mar-2018].

[20] D. Crawley and L. Lawrie, 'climate.onebuilding.org', 2018. [Online]. Available: http://climate.onebuilding.org/default.html. [Accessed: 01-Mar-2018].

[21] 'World Bank Open Data | Data'. [Online]. Available: https://data.worldbank.org/. [Accessed: 01-Mar-2018].

[22] X. Qiu, F. Yang, H. Corbett-Hains, and M. Roth, 'ASHRAE Research Project 1561-RP Procedure to Adjust Observed Climatic Data for Regional or Mesoscale Climatic Variations', American Society of Heating Refrigerating and Air-Conditioning, 2015.

[23] L. Lundström, 'Mesoscale Climate Datasets for Building Modelling and Simulation', in *DIVA*, 2016, vol. 9.

[24] L. Lundström, 'Shiny weather data', 2017. [Online]. Available: https://rokka.shinyapps.io/shinyweatherdata/. [Accessed: 01-Mar-2018].

[25] R. Gelaro *et al.*, 'The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)', *J. Climate*, vol. 30, no. 14, pp. 5419–5454, May 2017.

[26] Global Modeling and Assimilation Office, 'MERRA-2 tavg1_2d_slv_Nx: 2d,1-Hourly,Time-Averaged,Single-Level,Assimilation,Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC)', *International Centre for Tropical Agriculture (CIAT)*, 2015. [Online]. Available: DOI:10.5067/VJAFPLI1CSIV. [Accessed: 01-Mar-2018].

[27] Z. Qu *et al.*, 'Fast radiative transfer parameterisation for assessing the surface solar irradiance: The Heliosat-4 method', *Meteorologische Zeitschrift*, pp. 33–57, Feb. 2017.

[28] M. Schroedter-Homscheidt *et al.*, 'User's Guide to the CAMS Radiation Service', CAMS72_2015SC2_D72.1.3.1-2017_UserGuide_v1, 2017.

[29] U.S. Department of Energy, 'Residential Prototype Building Models', 2013. [Online]. Available: https://www.energycodes.gov/development/residential/iecc_models. [Accessed: 01-Mar-2018].

[30] A. Jarvis, H. I. Reuter, A. Nelson, and E. Guevara, 'Hole-filled seamless SRTM data V4', *International Centre for Tropical Agriculture (CIAT)*, 2008. [Online]. Available: http://srtm.csi.cgiar.org. [Accessed: 01-Mar-2018].

[31] F. Rubel, K. Brugger, K. Haslinger, and I. Auer, 'The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100', *Meteorologische Zeitschrift*, pp. 115–125, Apr. 2017.

[32] M. Kottek and C. B. J Grieser, 'World Map of the Köppen-Geiger climate classification updated', *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.